Autonomous Inspection using an Underwater 3D LiDAR

Dan McLeod and John Jacobson
Lockheed Martin MST
Houston, TX

Mark Hardy and Carl Embry
3D at Depth
Denver, CO

Abstract

Advances in autonomous inspection of subsea facilities using a 3 Dimensional(3D) LIght Detection And Ranging (LiDAR) sensor are examined to illustrate the favorable enhancement of safety, reliability, reduction in risks, economic benefits and superior data products compared to conventional means. These benefits provide operators with significant improvements over general visual inspection by the addition of sensors that produce 3D models of the structure being inspected. Examples are provided illustrating test data from operations conducted from 2012-2013.

Supported by funding from the Research Partnership to Secure Energy for America (RPSEA) Lockheed Martin MST teamed with the innovative company 3D at Depth to incorporate their new DP2™ 3D LiDAR onto the proven Marlin® Autonomous Underwater Vehicle. The objectives of the project include:

Survey using combination of high resolution 3D Sonar and 3D LiDAR

Generation of high fidelity 3D models Detection and localization of structural changes vs. reference model

Lockheed Martin has successfully integrated the laser into the Marlin shore based laboratory addressing the challenges associated with coordinating a scanning laser from a moving platform and producing high resolution georegistered images. Testing will be conducted in early 2014 to validate the system in the Atlantic Ocean waters offshore Palm Beach, Florida. Three dimensional georegistered models of an entire scene can be rapidly collected providing a clear vision of the underwater scene along high resolution 3D models of the imaged item.

Data collected at sea and in the laboratory will be presented demonstrating the performance of the system.

Application to deepwater life of field inspection will be presented with evidence gained from offshore trials. This emergent technology supports Subsea Facility Inspection Repair and Maintenance, Integrity Management Inspections of Marine Risers, Moorings and anchors, Subsea Pipelines, Flowlines, Umbilicals, and supporting subsea infrastructure.

Keywords-Imaging, Autonomous, AUV, Lidar, 3D, Subsea, Underwater, 3D Mode, Subsea Field, IMR, Inspection, IRM, Laser

I. INTRODUCTION

Frequent risk based assessment of the condition and integrity of subsea equipment is vital to predicting the life of the equipment and prevention of uncontrolled release of hydrocarbons into the environment. Oil and Gas operators must know the state of the equipment that is often thousands of meters below the ocean surface shrouded in the veil of darkness. Traditional means of inspecting this equipment employs visual sensors such as video or still cameras mounted on Remotely Operated Vehicles (ROVs) that are hardwired to the operators controlling the vehicle from a ship above the inspection site. This General Visual Inspection (GVI) requires significant topside support equipment and numerous skilled operators on site to control observe and maintain the ROV and interpret the images along with a large vessel support crew. While the quality of images has improved with the advent of digital High-Definition or HD sensors the images are often degraded by movement of the cameras and the turbidity of the water, reducing the effectiveness of the inspection. In addition, the data provided to clients is hours upon hours of recorded video that must be archived and revisited by humans for detailed examination.

With the advent of 3 Dimensional (3D) imaging sonar and 3D Light Detection and Ranging (LiDAR) the visual images can be augmented or replaced altogether with 3D models of the subsea equipment geolocated in their respective positions on the seabed. These 3D models can be imported into a variety of third party software tools that permit detailed engineering analysis of the structures and even real time change detection.

Today, the use of 3Dsonar and 3D LiDAR has been relegated to deployment on tripods set on the seabed offering a stable platform. This approach results in a limited field of view both horizontally and vertically essentially imaging one portion of the scene at a time. To image an entire structure requires the tripod to be moved incrementally gradually encompassing the entire structure in the view of the sensor. The images are then post processed into a mosaic revealing only the area that could be covered by the sensors viewing field. When mounted to an ROV the sensors must be stabilized by the ROV fixing itself to a stable structure and/or sitting on the seabed while

978-0-933957-40-4 ©2013 MTS

measurements are made. Both of these techniques produce limited incomplete views of the scene resulting in limited information to the client. This technique also requires multiple repositioning of the sensor and significant post processing to generate a final image.

Lockheed Martin Engineers have developed the Marlin® Autonomous Underwater Vehicle (AUV) (Fig. 1) that not only carries the sensors, but also interacts with the sensors and the vehicles navigation and control system to produce high quality motion compensated 3D models within minutes of retrieving the vehicle to the surface (1). "3D imaging on the fly" enables users to collect a god's eye view of the subsea field with accurate 3D modes generated for every structure imaged over the course of a data collection mission. These models are not limited to the scanning field of view of a tripod mounted sensor and leveraging our patented Feature Based Navigation system the models are accurate to millimeters or centimeters depending on the 3D sensor employed.

Fig. 1. Lockheed Martin Marlin AUV Operating the Gulf of Mexico

Lockheed Martin and 3D at Depth are teamed to incorporate the DP2™ 3D LiDAR onto the proven Marlin AUV resulting in a transformational capability to produce georegistered 3D images of subsea equipment "on the fly" with millimeter resolution.

This work is partially funded under a Department of Energy contract administered by the Research Partnership to Secure Energy for America (RPSEA).

The development of the sensor and the plans to integrate and test using the Marlin AUV are described below.

II. UNDERWATER LIDAR BACKGROUND

There are currently two methods used by underwater LiDARs to determine range: Triangulation and Range Gated (Time of Flight) based techniques.

In the last 2-3 years, a number of companies have released underwater laser imaging devices for the inspection market, all of these devices are based on triangulation technology. Triangulation based sensors provide very high spatial and range resolution at short range, but due to the fundamental technology (a geometry approach to calculating range) the errors of the depth measurement grow exponentially with range. This is why the terrestrial laser scanners on the market today are not triangulation based.

3D at Depth's underwater laser imager is based on Time of Flight (ToF) technology which is the same technology used in many of the terrestrial laser imagers. As the name implies, this technology measures the time from the sensor to the target and back, thus it is not fundamentally range limited (ToF LiDARs are used to measure range to satellites).

A. Triangulation Sensors

As a general rule, triangulation based sensors will provide higher resolution (< 1mm) than ToF sensors for very short ranges (< 1m). There is a transition between 1- 2.5 meters where the ToF sensor will start to provide better performance (3D at Depth has demonstrated ~ 1.5mm range precision in our test tank). Above 2.5 meters range, ToF sensors generally provide more accurate results (3D at Depth demonstrated ~ 5mm range precision at 8m range in our test tank).

When starting our sensor development, 3D at Depth investigated triangulation based sensors, but based on customer feedback it was determined that the range was too limiting. Our customers did not want the risk of being 1-2 meters from an expensive underwater asset in order to perform inspections. In addition, the longer range allowed for a larger field of view (inspection area) and allowed for the Inspection Vehicle to travel faster since it could be several meters from the asset, thus reducing concerns of collisions (such as in pipeline inspections). This was deemed a key requirement for the sensor.

A literature search reveals that both triangulation and range gated (or Time of Flight) underwater systems have been investigated over the last several decades. The list of references is too long for the purpose of this document, so only a few of the more recent ones are referenced.

Laboratory versions of triangulation based laser imagers in clear water and short range (0.2m -0.4m) were developed and demonstrated in the mid-1990s. (2) (3)Even at that time, triangulation systems were noted for providing high resolution at close range (< 3m), while range-gated systems could provide better resolution at longer ranges.

A triangulation based system was developed by K. Moore at the Scripps Institute of Oceanography in 2000 for bathymetry (4). This system was designed to provide ~3 mm accuracy depth information at 2m range that degraded exponentially with range. Depth resolution errors would approach 10cm at 10 meter range.

More recently, another triangulation system was developed for seafloor roughness measurements. This system operated ~75cm above the seabed and produced ~0.3mm(x) x~0.5mm(y) x ~0.3mm (depth) resolutions while deployed off the New Jersey coast (5).

Note that the range is generally less than 3m for these triangulation systems. This is a fundamental limitation of the triangulation method and is best explained by understanding the geometry that is used to calculate the range to an object. Fig. 2 below and the following text depict the base geometry and nomenclature for a triangulation system (all borrowed from [4]).

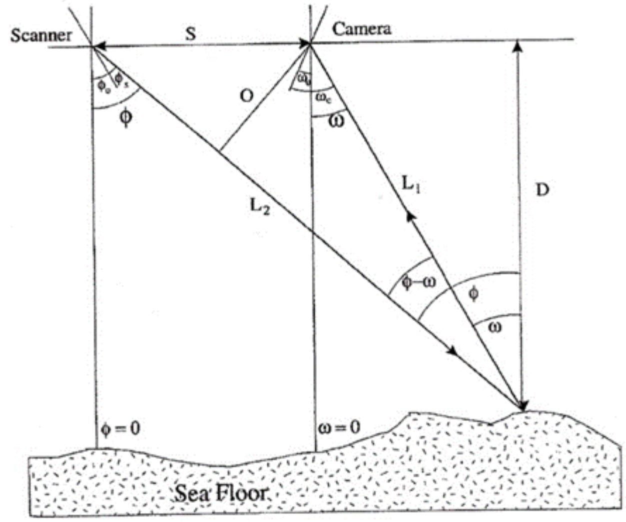


Fig. 2. Basic Geometry for a Triangulation Based Laser Imager (4)

$$D = \frac{S}{\tan(\phi_s + \phi_o) - \tan(\omega_c + \omega_o)} \quad (1)$$

Based on this geometry, (1) is used to calculate the range from the sensor to the object where D is the depth (range) to be measured, S is the distance from the laser source to the camera (baseline), ϕ_S is the laser beam angle ϕ_O is the offset-mounting angle of the laser housing, ω_O is the offset-mounting angle of the camera housing, and ω_C is the pixel-viewing angle with respect to the camera housing. The pixel viewing angle is a function of the pixel position p_j in the sensor array.

If the viewing angle subtended by each pixel in the array is Ω_p, then $\omega_c = \Omega_p\, p_j$. If the laser is scanned, then the scanner mirror position is a function of voltage and the laser beam angle $\phi_s = kv_j$ where v_j is the scanner voltage that corresponds to pixel j, and k is an empirically determined constant. Therefore, the depth of sample j can be expressed as

$$D_j = \frac{S}{\tan(kv_j + \phi_o) - \tan(\Omega_p p_j + \omega_o)} \quad (2)$$

Note that since the scanner-camera separation distance (S) and mounting angles (ϕ_o and ω_o) are assumed to be fixed, the baseline distance and mounting tilt angles must be stable again shock and extreme pressure. Assuming they are fixed, only the laser beam positional accuracy $\Delta\phi_s$, and pixel position accuracy $\Delta\omega_c$ determine range performance.

The range resolution ΔDepthj can therefore be expressed as

$$\Delta Depth_j = \left[\frac{S}{\tan(kv_j + \phi_o + \Delta\phi_s) - \tan(\Omega_p p_j + \omega_o + \Delta\omega_c)}\right] - Depth_j \quad (3)$$

While $\Delta\phi_s$ is dependent solely on mechanical (mounting) or electronic limitations, $\Delta\omega_c$ is only partially described by the angular resolution of each pixel. It is also influenced by laser beam divergence, target reflectance properties, and the scattering properties of the water body itself.

B. Time of Flight Sensors

Many of the terrestrial laser imagers available on the market today are based on Time of Flight (ToF) technology. This includes products such as the Leica ScanStation C10, the Trimble CX Scanner, and the Optech ILRIS-3D. These ToF sensors use a laser to emit a pulse of light. An accurate timer is used to time how long it takes for the pulse of light to travel to and from a target. This time is then used to calculate the range to the target based upon the speed of light.

There is no fundamental limitation on the range of a ToF sensor besides the ability to detect the return photons reflected off the target (ToF LiDARs are used to measure the distance to satellites). Therefore highly reflective objects can be detected at longer ranges than low reflectivity targets. Range precision is based upon the fundamental range resolution of the sensor (usually defined by the pulse width of the transmit laser), the signal to noise ratio, and the number of averages (if any). Spatial precision is based upon the transmit beam size and scanner angular control. Therefore both range precision and spatial precision will degrade with range.

There is another class of terrestrial scanners called phase-shift. These scanners emit a continuous beam of laser light that is amplitude modulated. By calculating the phase of the return waveform in relation to a local copy of itself, range can be calculated. This technology has a fundamental limit on range (called the range ambiguity); however the newer systems are pushing the range ambiguity out to > 70 meters (Surphaser 25HSX). The range precision of the phase-shift sensor is defined the same as a ToF sensor.

A literature search will reveal that scanning, pulsed, 3D laser imagers have been investigated and deployed underwater over the last couple of decades for military purposes (6) (7) (8) (9). Some of these are underwater based and others are aircraft based to detect underwater mines. In either case, the systems described do not attempt to achieve the range and spatial accuracies provided by current terrestrial laser scanners.

C. Other Laser Sensors

This section briefly discusses two other technologies available on the market although they are not 3D laser imaging technologies

1) Laser Line Scan System

SAIC used to offer a product called the SM2000 Laser Line Scan System, but the system is no longer listed on their website. This was a laser line scanning system that generated high resolution 2D images at up to 20 meter range. Since this sensor was in effect a high resolution video camera (no range information), it is a fundamentally different product than the sensors discussed in Sections 2 & 3. However, it is a good existence proof of a deployed scanning laser system that acquired high spatial resolution images underwater at ranges up to 20 meters.

2) High Resolution Multi-Beam Sonar

Multibeam imaging sonar products provide high performance imaging sonar capabilities in compact, low power systems. The primary advantage of the acoustic system is its ability to perform in highly turbid water conditions, unlike an optical sensor. Since the ultra-deep water environment usually has good visibility conditions (as shown by ROV cameras), this ability is less of an advantage in ultra-deep water projects. The primary disadvantage is the resolution of the acoustic system: ~1cm range accuracy and ~ 3cm spatial resolution at the 10m max range (compared to < 1mm for a laser sensor

D. 3D at Depth Sensor

3D at Depth's goal is to bring the terrestrial laser imaging capability subsea, thus providing the same cost saving in construction, maintenance, inspection, repair, and retro-fits as has been realized top-side. Through discussions with industry we determined that our sensor needed to have a range of at least 5 meters. Customers did not want the risk of being 1-2 meters from an expensive underwater asset in order to perform inspections. In addition, the longer range allowed for a larger field of view (inspection area) and allowed for the Marlin to travel faster since it could be several meters from the asset, thus reducing concerns of collisions (such as in pipeline inspections). This was deemed a key requirement for the sensor because in many applications increased speed equates to reduced costs. This range requirement eliminated triangulation technology options.

When reviewing the terrestrial laser imager technologies of ToF or phase shift, a pulsed system has distinct advantages over a continuous-wave (phase shift) technology underwater. When using the continuous beam of light for a phase shift sensor, the continuous back-scatter from the water creates added noise since the sensor is receiving light from the entire water path. With ToF imagers the sensor only receives backscatter from the water at the location of the pulse of light at any instant in time. For this reason 3D at Depth's technology is ToF based.

Although ToF and phase-shift technologies are well understood in the atmosphere, the extreme scattering and variability of underwater conditions requires numerous modifications to the basic technology. 3D at Depth has focused on understanding the unique requirements needed for a laser imager to maintain sub-cm accuracies underwater (and has patents pending on this technology).

Table 1 shows the predicted range precision and spatial resolution performance for the ToF laser imager that will be built under the RPSEA Phase 1 program. Table 1 includes range precision estimates for both Jerlov Type III water (oceanic water at temperate latitudes) and Jerlov Type I water (extremely clear oceanic water). This sensor was designed to provide 1cm range precision at 8 meter range in Jerlov Type III water (conservative for ultra-deep water operations).

TABLE 1. Theoretical Performance for 3D at Depth Sensor for Two Different Water Conditions

Range (m)	Spatial Resolution (mm)	Range Precision (mm) Jerlov Type I	Range Precision (mm) Jerlov Type III
2	< 1	< 5	< 5
5	<1	< 5	< 5
8	<1*	< 5*	< 10
10	<1	~5	~30
12	~1	~6	N/A
15	~3*	~10	N/A

*Demonstrated with lab prototype in test tank

Note that the models predict < 1mm spatial resolution and < 5 mm range precision at close range. However 3D at Depth is reluctant to promote that level of accuracy until demonstrated in open water conditions.

III. CHALLENGE

Given the precision placement and small diameter of LiDAR spot size the high scan rate and the potential distortion of an image resulting from sensor motion a tight coupling of the LiDAR sensor with the Marlin AUVs motion is required to produce accurate 3D models.

Our team's goal is to:

- Collect high precision georegistered image points underwater
- at a rate of 40000 points per second
- while traveling at two knots
- processing the data in real time
- building a 3D image on-the-fly

IV. APPROACH –

Using software algorithms developed for LiDARs mounted on land based vehicles Lockheed Martin engineers produced amazing 3D models from point clouds generated using the Coda Octopus Echoscope sonar (10) (11). Lockheed Martin is now adapting the proven sonar software to process the DP2™ LiDAR point clouds to generate 3D models on-the-fly (Fig. 3).

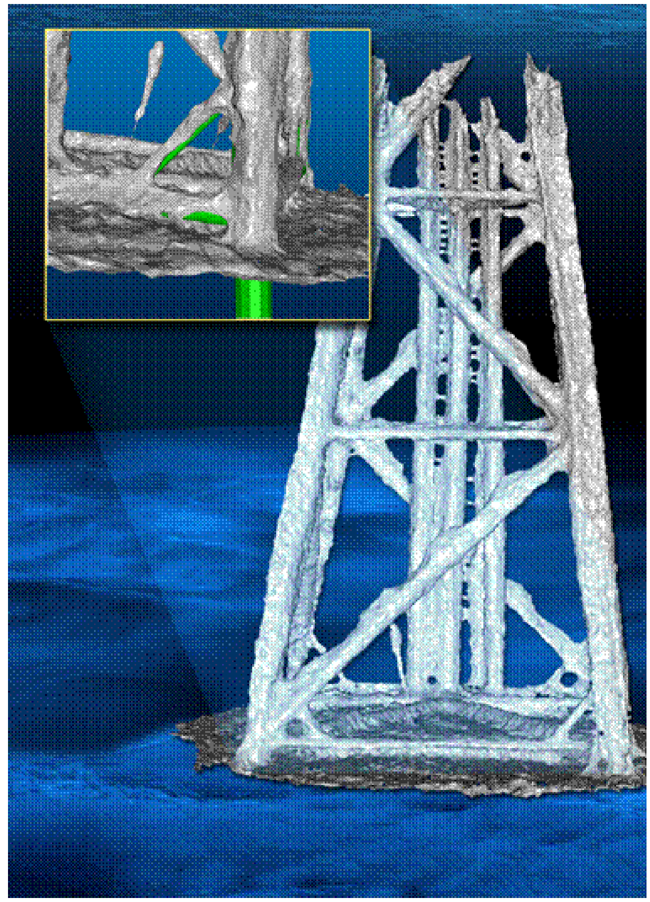


Fig. 3. 3D Sonar Image of a 4 Pile platform in the Gulf of Mexico. The image was generated autonomously using the Marlin AUV Structural Survey System

Testing conducted by 3D at Depth and their partners has confirmed the performance of the DP2 product baseline while operating in a number of environments reducing the complexity and difficulty integrating the DP2 onto the Marlin.

V. LAB TANK AND OFFSHORE TESTING

De-risking of offshore operations start with a laboratory simulation that incorporates georegistered 3D models of the subsea scene and bathymetry, vehicle motion and trajectory, simulated models of the actual laser performance (transmission and scattering) in the sea water medium, simulated performance of the DP2™ 3D LiDAR, and the onboard signal processing used by the Marlin Figure 4.

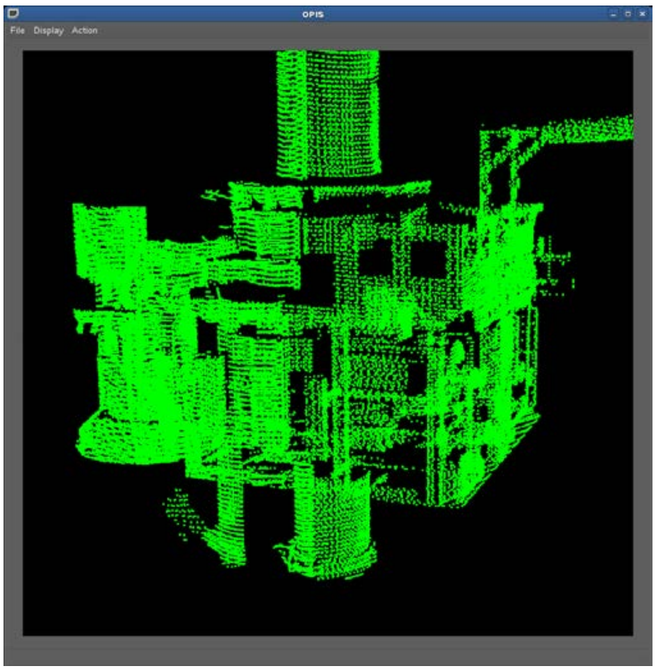


Fig. 4. Simulated DP2 Image of a subsea wellhead. Imaged while mounted on a Marlin AUV moving at 2.0 kts.

3D at Depth and their partners have conducted tests against varying targets common to the subsea oil field (12) including freshwater tanks Figure 6 and Figure 7, salt water tanks, and in a deep water Gulf of Mexico field Figure 5.

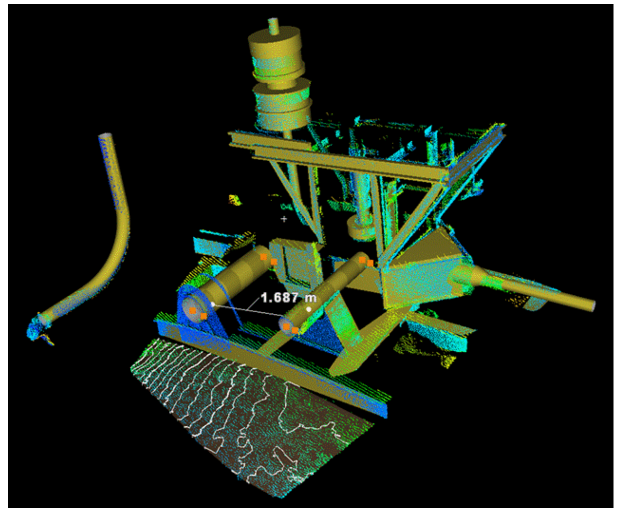


Fig. 5. Composite image generated by InScan LiDar of a deep water pipeline end termination.

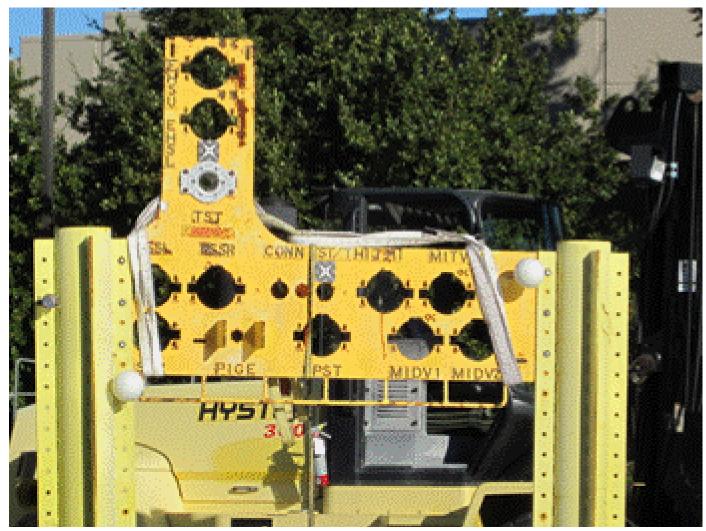


Fig. 6. Mockup hot stab panel used as a target for tank testing of the InScan LiDAR.

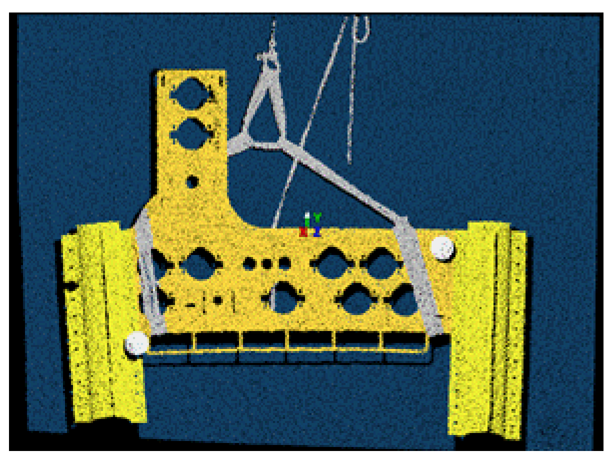


Fig. 7. Processed InSCAN image of the hot stab target generated in a fresh water test tank

A series of test cases have been developed to allow the engineers to examine the performance of the system across a range of varying parameters. Each test run produces 3D models of the subsea field providing confidence in the performance before ever going to sea. This same approach was used successfully in the development of the Marlin using the Coda Octopus Echoscope® 3D sonar.

After successfully passing the rigors of laboratory testing the software is then integrated to the final hardware in our integration lab prior to dockside and local at sea testing. This process greatly reduces the development errors encountered at sea and also provides a means of playback of field generated data for resolution of faults encountered at sea.

VI. BENEFITS

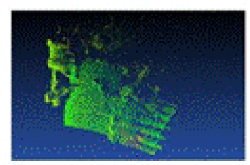
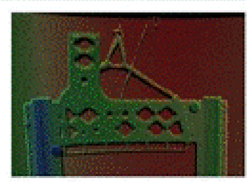
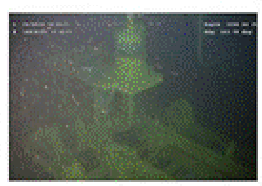
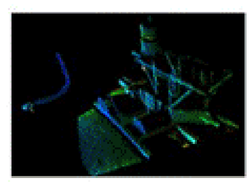
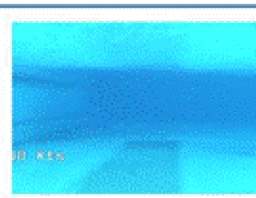
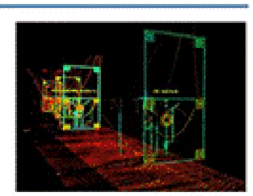
Advances in underwater imaging using LiDARs open new capabilities to generate high resolution 3D models of subsea structures. 3D at Depths DP2 LiDAR, the Marlin variation of the InSCAN, integrated with the Marlin AUV's proven ability to generate 3D models based on sonar images now brings the Offshore Oil and Gas industry a powerful new tool.

High resolution 3D models can be generated on-the-fly using the Marlin as the host platform for the DP2 Lidar. Table 2 shows the performance of the DP2 LiDAR in varying conditions as compared to video images of the same scene.

3D Models of subsea structures offer the field operators engineers an engineering tool versus simple images. The models can be used for

- Metrology; the ability to determine dimensions directly from the model versus extrapolating from still images
- CAD Modeling including structural and thermal analysis
- Rapid assessment of the condition of the structure due to damage or installation problems
- Automated change detection upon subsequent surveys

TABLE 2. 3D at Depth InSCAN LiDAR performance in varying conditions against varying targets.

Visibility	Range	Data collection	Video Image	Processed Point Cloud Image
Poor	2-4 meters	ROV Mounted tests conducted in Gulf of Mexico. Small areas of interest from close range are difficult to register together		
Fair	5-10 meters	Tank Testing Multiple setups: accuracy ≈ 2 cm*		
Good	10-20 meters	ROV Mounted tests conducted in Gulf of Mexico . Two setups: accuracy ≈ 7 mm*		
Excellent	20-40 meters	OMSET Tank Testing. Single setup: Accuracy ≈ 1- 3 mm*		

*measuring a point to point distance of over 30 meters

ACKNOWLEDGMENTS

This work is being conducted with partial funding under a Department of Energy contract administered by the Research Partnership to Secure Energy for America (RPSEA) with direct oversight and inputs from RPSEA Project Manager Mr. Donald Richardson.

The authors would like to acknowledge the entire Lockheed Martin and 3D at Depth teams for their professional and tireless efforts to advance technology.

REFERENCES

[1] **Tangirala, S., et al.**, "Integrated Autonomy for the Inspection of Underwater Structures Using Autonomous Underwter Vehicles"**.**, **AUVSI** Washington : s.n., AUVSI11, 2011..

[2] **Cami, F. M., Kocak, D. M. "***Real-time 3D underwater imaging and mapping using a laser line scan technique."* s.l. : SPIE Opt. Scan. Syst.: Design Appl., pp. 241-252, 1997..

[3] **Smith, F. M. and Caimi, D. C.** US Patent, *5,418,608* USA, 1995.

[4] **Moore, K. D., Jaffe, J. S. and Ochoa, B. L. "***Development of a New Underwater Bathymetric Laser Imaging System": L-Bath.* Journal of Atmospheric and Oceanic Technology, 17, pp. 1106-1115., 2000

[5] **Tang, C. C. and Wang, D. "***Seafloor Roughness Measured by a Laser Line Scanner and a Conductivity Probe"*., IEEE Journal of Oceanic Engineering, Vol. 34, No 4, pp. 459-465. Oct. 2009

[6] **McLean, J.W.** "*High Resolution 3-D Underwater Imaging",* SPIE Conference on Airborne and In-Water Underwater Imaging", Vol. 3716, 10-19, 1999.

[7] 7. **Ulrich, et. al.** *Imaging Lidar System. 4.964,721* United States of America Patent, 1990.

[8] **Acharekar, M.** "*Underwater Laser Imaging System (ULIS".* 1997, SPIE, Vol. 3079, pp. 750-761.

[9] **McHale, J. "***Navy moves to Ladar for Minehunting",* , Military & Aerospace Electronics, Vol. 8, p. 1., 1997

[10] **McLeod, D. L. and Jacobson, J. R.** "*The Role of Autonomous Underwater Vehicles in Deepwater Life of Field Integrity Management."* Rio de Janeiro : Offshore Technology Conference. 2011.

[11] M**cLeod, D., Jacobson, J. R. and Tangirala, S***Autonomous Inspection of Subsea Facilities - Gulf of Mexico Trials",* Houston : Vols. OTC-23512, 2012..

[12] Embry, C., Hardy, M., Nickerson, G., Manning, N., Richardson, D., Pappas, J., "high-Resolution 3D Laser Imaging for Inspection, Maintenance, Repair, and Operations", Houston: Offshore Technology Conference, 2013